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THE CRYSTAL COUNTER

A NEW APPARATUS IN NUCLEAR PHYSICS FOR THE INVESTIGATION OF β- AND γ-RAYS. PART II

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Synopsis

AgCl crystals were irradiated with monochromatic β-rays in a magnetic β-ray spectrograph. The results show that under suitable experimental conditions in the crystal all β-rays of a certain energy cause ionisation pulses of the same value within the errors of measurement. The magnitude of an ionisation pulse is proportional to the energy of the β-particle. This means that the amount of energy necessary for the formation of one conduction electron is independent of the energy of the β-rays. This amount was found to be 7,6 eV.

The measurements of the ionization pulses caused in AgCl by α-rays showed that many of the α-particles caused an ionization pulse smaller than normal. We ascribed this effect to a thin irregular surface layer which is less effective than the crystal's interior. Many of the crystals we investigated showed a thicker surface layer. This layer also influenced the ionization by β-particles, which then showed the same effect as the α-rays. The nature and the circumstances under which this hypothetical surface layer appears or can be removed are not yet clear and still form a point of investigation.

§ 1. *Apparatus.* As the preliminary experiments described in Part I did not yield definite results, it was necessary to investigate the crystals by homogeneous β-radiation. A general lay out of the experimental arrangement is given in fig. 1: A glass cylinder of 1 cm thickness and with a diameter of 30 cm stands on a flat disk. The β-spectrograph is the one already used by Ten Kate [2]). The cylinder is closed at the top by a metal plate. The plate has a circular hole. This hole is closed by the tube in which the crystal is mounted and by which the crystal is cooled. The β-ray spectrograph is made air-tight by rubber rings between the ground plate, the cylinder and the upper plate. A rubber ring is also fitted between the tube which holds the

crystal and the upper plate. A hole in the middle of the ground plate leads to the vacuum pump. In order to avoid scattering of the β-rays in the gas, the pressure needs only to be kept below 1 mm, but as we put a high voltage, up to 3000 Volts, on the crystal, to avoid discharges in the gas it is necessary to evacuate the spectrograph to 10^{-5} mm. The use of rubber rings guarantees a good vacuum. The β-ray source consists of radium E, deposited on a thin platinum wire. A homogeneous beam was selected by screens of aluminium of 3 mm thickness, as shown in fig. 2. The radius r of the semicircle is 9,1 cm. The slits in front of the crystal have a width of 3,5 mm. The width d of the diaphragm D is adapted to this value according to the formula

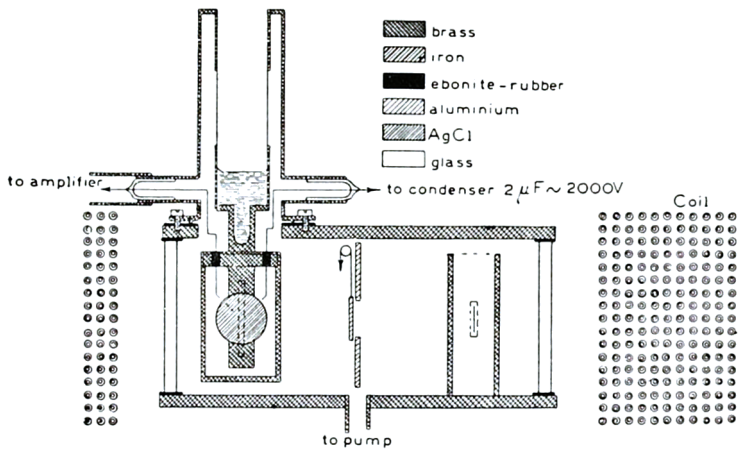

Fig. 1. The magnetic β-ray spectrograph and the tube holding the crystal.

$d^2 = 2rs$, so that $d = 2{,}5$ cm. From Ten Kate's [2]) calculations, it follows that the intensity of the radiation is proportional to d, but an increase of d causes a decrease of the homogeneity of the β-radiation. We obtain a maximum of intensity for a given homogeneity when d is chosen according to the formula mentioned. (The same considerations determine the most economical height of the diaphragm of the slit, but in our arrangement a smaller height was chosen, defined by the dimensions of the crystal).

The diaphragm in the centre is fitted with a shutter that can be opened by hoisting it by a thread. The end of the thread is coiled on a spindle fixed to a glass joint in the pump barrel. The magnetic field is supplied by the electric current in a coil of hollow copper tube,

through which water runs for cooling. The advantage of avoiding the use of iron poles is that we have plenty of room for the spectrograph. Moreover, the magnetic field is strictly proportional to the current in the coil, so that it is only necessary to calibrate the field strength for one value of the current. This had already been done by Ten Kate[2]), who found it to be 6,93 Oerstedt Ampère at a distance of 9,1 cm from the centre. We can send a steady current of 80 Ampères through the coil and thereby we obtain homogeneous β-rays up to 5.700 H = (1 MeV). We obtained the current from the 220 Volt

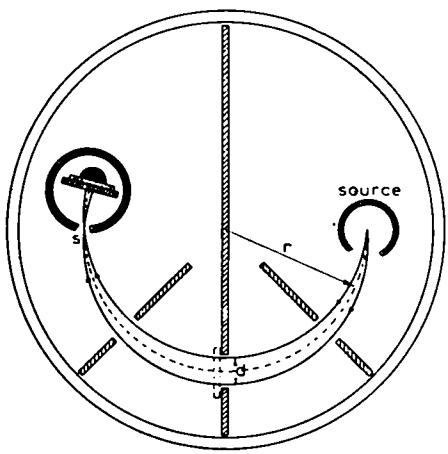

Fig. 2. The magnetic β-ray spectrograph.

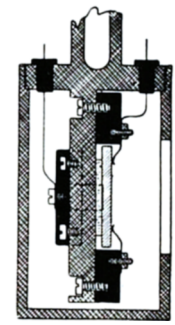

Fig. 3. Lower part of the tube holding the AgCl crystal. (See fig. 1).

storage battery of the laboratory. The lower part of the tube in which the crystal is mounted is shown in fig. 3. Liquid air was poured into the inner tube. Cotton wool prevented bubbling that would have a microphonic effect. The inner tube is made of iron, (a metal which is a bad conductor of heat) turned off to 0,2 mm to make the thermal losses to the surroundings as small as possible. The bottom of this tube is formed by a piece of brass upon which the crystal is fixed by silver clips. The silver clips are fixed on pieces of ebonite. The crystal is electrically insulated from the brass by a plate of quartz, which is a relatively good conductor of heat. The crystal is screened off from the surroundings by a brass tube, nickel-coated on the outside in order to reflect the thermal radiation. In this tube is a slit through which the β-rays can pass.

Experiments show that without additional measures in this arran-

gement the amount of heat conducted from the crystal to the liquid air is much too small to be cooled within a reasonable time. This is due to the fact that the transport of heat from one body to another body pressed against it mainly passes through the air between the two, since the actual contact of the bodies is established by relatively small areas, having a large heat resistance. When the diameter of the contact area is a, and the heat resistance of 1 cm^3 of the body is c, then the heat resistance of a contact will be of the order of c/a. Apparently, the areas of real contact of two bodies pressed against each other, are very small. Consequently, the heat resistance becomes very large, when the tube is evacuated. We used therefore paraffin oil to make contact between all surfaces, where good thermal contact had to be made. In this way the cooling was greatly improved and we could start the observations after 40 minutes of cooling.

A thin steel wire, screened off by a metal tube, connects the crystal to the first valve. The table on which the β-ray spectrograph, the mercury pump and the first valve of the amplifier are mounted was placed on rubber cushions to avoid mechanical vibrations. The rest of the apparatus is the same as described in part I.

§ 2. *Experimental results.* In figure 4 the distribution curve is given for the deflections obtained with homogeneous β-radiation of

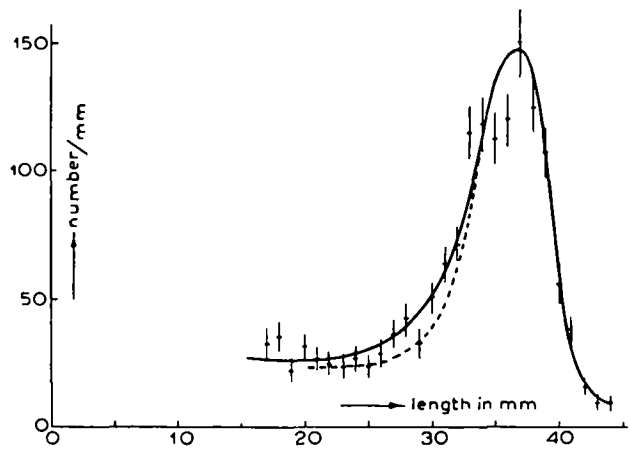

Fig. 4. The distribution curve of the deflections caused by homogeneous β-rays. $H\rho = 2500$; $E = 0{,}4$ MeV; $V = 200$ Volt; 1 mm = 1200 e.c. Dotted: curve expected theoretically.

$H\varrho$=2500. It shows one peak, which goes down to zero on the side of the large deflections. On the other side there is a relatively low level of smaller deflections. As we shall show, the shape of the curve can be explained almost completely. The peak is formed by β-particles which are completely absorbed in the crystal, and all of which cause the same ionization pulse. The width of the peak can be explained by the sources of measuring errors discussed below. The "tail" of the curve is caused by reflected β-particles, which have lost only part of their energy in the crystal. The dotted curve is the one which can be expected by theory if we take into account all sources of error. The small deviation from the real curve on the side of the small deflections will be discussed below.

The sources of errors. Thc sources of errors, discussed already in part I, are the following:

1. The noise of the amplifier. 2. The influence of the deflections on each other. We have determined the influence of these two sources

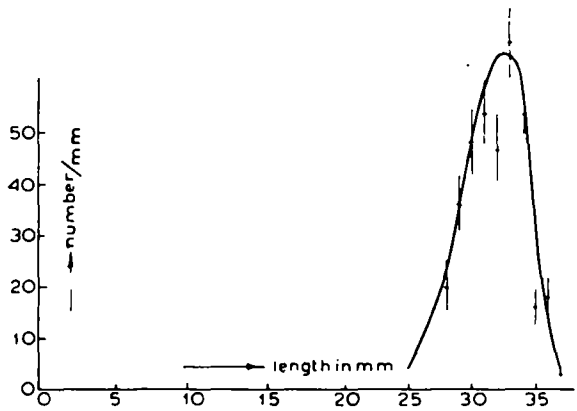

Fig. 5. The distribution curve of artificial pulses.

by measuring the dispersion of the deflections caused by a number of artificial charge pulses of the same magnitude, given in the opposite direction. In figure 5 the distribution curve of these deflections is given. We found a root mean square error of 5,3%. 3. The different depth of penetration of the β-rays in the crystal. We estimated this error, with the aid of the absorption curves for β-rays given by M a d g w i c h [3]). The crystal we investigated was 1,7 mm thick. We estimated this error to be 3%. 4. The reflections of β-rays. Ac-

cording to the experiments assembled in the "Handbuch der Experimentalphysik", part XV, we assumed that 50% of the particles were reflected. No data about the energy distribution of this reflected radiation were available. We assumed therefore a homogeneous distribution over all values from zero up to the maximum. It is possible that a deviation of the real distribution from this hypothetical one forms the explanation of the small deviation of the experimental curve from the theoretical one. 5. The inhomogeneity of the β-particles. This quantity can be calculated from the dimensions of the spectrograph [2]). We found a value of 2%. 6. Every number n of the deflections in the interval of a mm has an accidental error of the

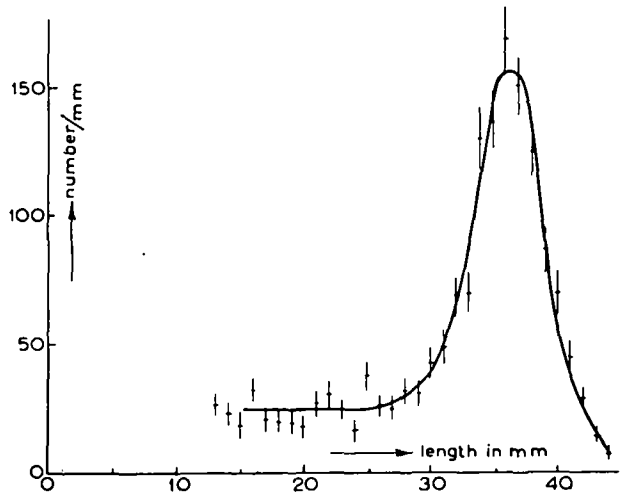

Fig. 6. A theoretical distribution curve.

order $\sqrt{n}$. 7. The "natural width" of the spectral line, that means: the accidental deviation from the mean value of the number of ions formed. As we discussed in part I, we expect this error to be less than 1% and consequently not observable in our arrangement. 8. The energy-losses in the silver electrode. The silver electrodes were about 0,15 mg/cm^2, while the mean depth of the penetration of the β-particles is 0,1 g/cm^2. This influence is considerately below 1%. 9. The stray radiation in the spectrograph. This effect was negligeably small in our arrangement.

For the total root mean square error we find 6,5%. To emphasize the influence of point 6, "measuring points" were determined by

adding an "accidental" error to the theoretical points; the theoretical curve, given in figure 6, is drawn through these "measuring points".

The result of the experiment is therefore that all β-rays cause indeed the same ionisation within the limits of errors of our experiments.

I o n i z a t i o n-e n e r g y r e l a t i o n. In figure 7 the relation is plotted between the magnitude of the ionization pulses in units of

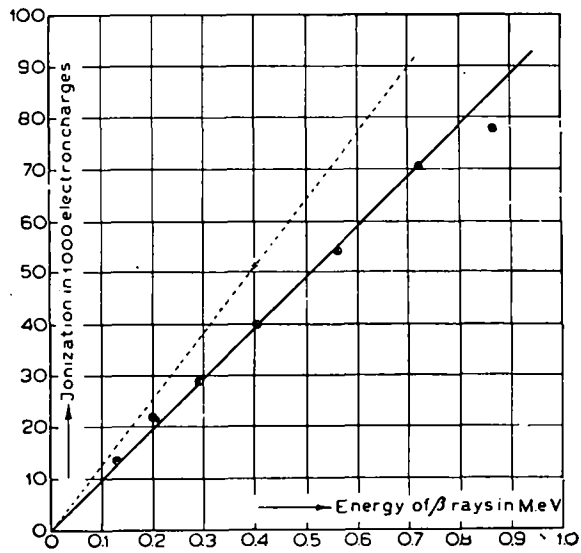

Fig. 7. The relation between the ionisation and the energy of β-rays. Dotted: the extrapolated saturation curve.

electron charges, and the energy E_β of the β-particles in MeV, according to the theoretical formula [4])

$$E = 0.511 \left[\sqrt{1 + \frac{2.89 \times 10^6}{(H\varrho)^2}} - 1 \right].$$

All measuring points were taken from the distribution curves for different values of $H\varrho$ by taking the maximum deflections diminished by the error we could expect from the causes 1 and 2. The line drawn through these points is straight. We find therefore that the number of ions formed by the β-particles is proportional to the energy. This

curve is not determined at saturation voltage. The dotted line in the same figure corresponds to the saturation value, that means to the real number of conduction electrons formed as a function of the energy. We determined this relation in the following way. For $E = 0{,}4$ MeV, we found the ionization pulse to be $N_1 = 40.000$ electron charges for $V_1 = 800$ volts and $N_2 = 45.000$ for $V_2 = 1700$ volts. With the aid of the saturation curve calculated by H e c h t[5]: $N = (\nu/\nu_0)\,(1 - e^{-\nu_0/\nu})$, we found a saturation value of $N_{max} = 52.000$ e.c. A straight line was drawn through this point and the origin giving the saturation curve for all energies. The energy E_0 necessary for the liberation of one conduction electron is independent of the energy of the β-rays, namely $E_0 = 7{,}6$ eV.

C o m p a r i s o n o f t h e i o n i z a t i o n i n c r y s t a l s w i t h t h a t i n g a s e s. When we compare these results with the measurements of the ionization in gases, we find some agreement between these two phenomena. In gases the total ionization of β-rays is also practically proportional to the energy [6]). For nitrogen for instance, the energy E_0 consumed in the formation of an ion is 36 eV [7]), while the ionization voltage E_i is 18 eV, so that $(E_0/E_i)_{N_2} = 2{,}0$ The ionization voltage for AgCl (given by the low frequency limit of the absorption spectrum) is 3,2 eV, so in this case $(E_0/E_i)_{AgCl} = 2{,}4$.

E x p e r i m e n t s w i t h α-p a r t i c l e s. In figure 8 the distribution curve is given for the pulses we recorded when the crystal was irradiated with homogeneous α-rays. The α-ray source, polonium, deposited on a platinum folium, was introduced into the β-ray spectrograph and could be moved in front of the slit by means of the same thread which hoisted the shutter. α-radiation is practically not reflected, so that we may expect the distribution curve to consist of one single peak. The experimental curve however shows a high level of deflections of a lower value, due to particles which in some way do not produce the full ionization. An obvious explanation of this phenomenon is that the crystal has a surface layer which is less effective and which has a different thickness at different points. This assumption can explain why some α-rays produce the full ionization, while others lose part of their energy in this surface layer and thereby will show an ionization defect. This surface layer is not formed by the silver electrode as the thickness of that electrode is only 3% of the range of the α-particles. Owing to the steep slope of the distribution curve on the side of the large deflections, which slope

can be considered completely as a perpendicular fall, distorted by errors of measurement, one can assume that the maximum deflections will indeed represent the full ionization. These maximum deflections u_α are calibrated directly with the deflections u_β of the β-radiation of 0,4 MeV. In this way we find that $u_\alpha/u_\beta = 2{,}31$. The energy of the α-particles of polonium is 5,2 MeV,so that we can calculate that an α-particle needs 5,6 times more energy for the liberation of one electron than a β-particle. This phenomenon is quite different from the results in gases. In gases the energy per ion formed, is about the same for α- and β-rays [7] [8]. As the initial mechanism of ionization must be quite analogous, it is probable that also in

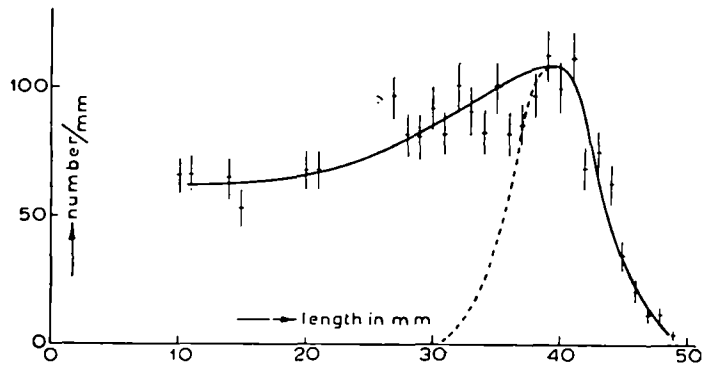

Fig. 8. Distribution curve of α-ray reflections of polonium; 1 mm 2100 e.c. Dotted: curve expected theoretically.

AgCl the number of electrons formed by a certain amount of energy is about the same for α- and β-rays. This result for AgCl resembles that obtained by J a f f é with ionization experiments in liquids such as hexane [9]. In hexane, the ratio of the energy per ion formed by α- and β-rays is 150. This value could be explained by J a f f é by assuming that originally this ratio is also unity, but that the ions formed by α-particles have a greater chance to recombine, owing to the high concentration of the ions. In AgCl we believe that we are not dealing with recombination, as the conduction electrons have a much larger mobility. We can give another explanation: The attractive field of the collection of ions formed on the conduction electrons is so large, that for a great part of the electrons the voltage put on the crystal is not able to overcome this force. We can calculate that

at a distance of 10 μ from the track of an α-particle (which has a length of about 10 μ) this attractive field is still 6000 Volt/cm, while the external field is of the same order. If this explanation is right, it would simply mean that the saturation curve for the ionization of α-particles is different from the curve for light or β-rays, and that saturation can only be reached for very high voltages. We found

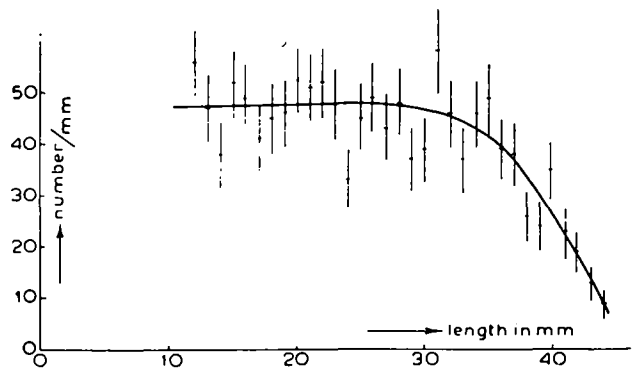

Fig. 9*a*. A distrbiution curve of α-ray reflections of polonium; 1 mm 330 e.c.

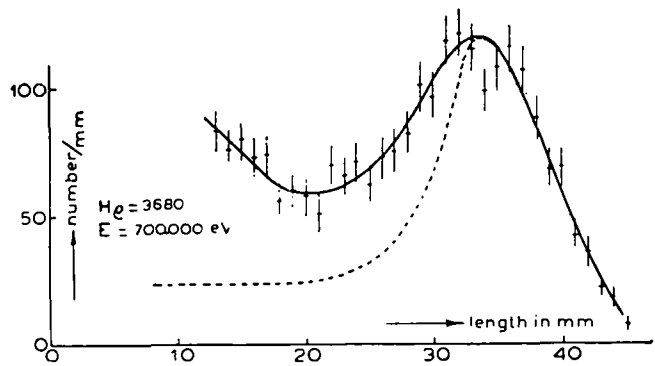

Fig. 9*b*. A distribution curve of β-ray deflections. $H\rho = 3680$.

already an indication of this effect. For the ratio between the energies necessary for the liberation of a conduction electron by α- and β-rays we found for $V = 800$ Volt a value of 5,6 and for $V = 1700$ Volt a value of 4,5.

P h e n o m e n a a s y e t n o t u n d e r s t o o d. Many of our crystals showed the phenomenon of the "ionization defect" much stronger, not only for α-rays but also for β-rays. In figure 9 some

distribution curves are given of these records. When we first compare the curve for α-particles with the curve of fig. 8, it is clear that the part of the rays which show the defect is much larger. But the β-rays show also a curve which clearly deviates from the dotted theoretical one. This can be explained by assuming that the ineffective surface layer is much thicker, so that a fraction of the β-particles also loses a large amount of energy in it. A check for this hypothesis is that the crystal that gave the correct results at first showed curves of the type of fig. 9. These correct results we obtained after removing a thick layer of the crystal. The nature of the hypothetical surface layer is not yet clear.

We must moreover admit, that we can not yet control the circumstances under which this layer appears or can be avoided, so that in this respect further investigations are necessary.

Conclusion. In the present article we have tried to develop a new instrument, the crystal counter, which not only detects radioactive particles but also measures the energy of every particle observed. We could show that in silver chloride the ionisation pulse caused by β-rays is exactly proportional to the energy, and so we succeeded, in principle, in showing the usefulness of the instrument.

Some phenomena, not yet understood, which can probably be ascribed to a less effective surface layer, still form a point of investigation. It is evident, however, that the real usefulness of the instrument must be shown in practice and also that this usefulness will be closely connected with the progress in solving another problem: the construction of sensitive instruments for the measurement of small electric charges.

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